Atmospheric Multiple Scattering Effects on GLAS Altimetry.

Part II: Analysis of Expected Errors in Antarctic Altitude Measurements

Ashwin Mahesh

Goddard Earth Sciences and Technology Center, Greenbelt MD

James D. Spinhirne

NASA Goddard Space Flight Center, Greenbelt MD

David P. Duda

Hampton University, Hampton VA

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Corresponding author address

Ashwin Mahesh
Mail Code 912
NASA Goddard Space Flight Center
Greenbelt MD 20771
Email: ashwin.mahesh@gsfc.nasa.gov

ABSTRACT

The altimetry bias in GLAS (Geoscience Laser Altimeter System) or other laser altimeters resulting from atmospheric multiple scattering is studied in relationship to current knowledge of cloud properties over the Antarctic Plateau. Estimates of seasonal and interannual changes in the bias are presented. Results show the bias in altitude from multiple scattering in clouds would be a significant error source without correction. The selective use of highly transmissive clouds or cloud-free observations, as well as improved analysis of the return pulse, such as by the Gaussian method used here, are necessary to minimize the surface altitude errors. The magnitude of the bias is affected by variations in cloud height, cloud effective particle size and optical depth. Interannual variations in these properties as well as in cloud cover fraction lead to significant year-to-year variations in the altitude bias. Although cloud-free observations reduce biases in surface elevation measurements from space, over Antarctica these may often include near-surface blowing snow, also a source of scattering-induced delay. With careful selection and analysis of data, laser altimetry specifications can be met.

1. Introduction

With increasing concern over warming of the earth's surface, the need to develop and implement sound monitoring programs to detect potential large-scale changes at an early stage has also grown. The high-latitudes, and the marginal ice zones around the frozen ice shelves there, have been a particular focus, in the expectation that the early signs of global change will be seen here, a view that has been bolstered by measurements of significant surface temperature changes in the coastal Antarctic and Arctic in recent decades.

A major goal of the orbital Geoscience Laser Altimeter System (GLAS) is to measure and monitor a particular aspect of climate change in the high latitudes, namely changes in the mass balance of the Earth's large ice sheets which are concentrated in the polar regions. Global warming could potentially alter the mass balance of these ice sheets, in turn leading to other climatic changes, notably a possible change in sea level. GLAS proposes to measure inter-annual changes in the thickness of polar ice sheets, and will provide the first estimates of continent-wide elevation changes in the Antarctic and Greenland ice sheets.

The determination of ice-sheet mass balance is limited by typical methods, which rely on a comparison of two large numbers - total snow accumulation and total ice loss - that are each subject to large errors. Recently, more accurate methods to measure the ice-sheet mass balance have been developed using repeated altimetry measurements of the ice sheets by airborne lidar [1] and satellite radar [2]. These new methods each contain drawbacks; radar measurements are sensitive to surface slope errors and radar penetration into snow, and relatively few airborne lidar measurements over Greenland and Antarctica have ever been attempted. GLAS measurements will mark an improvement on existing observations, and will record temporal changes in the thickness of the Earth's polar ice sheets from space [3].

GLAS is a laser-based surface altimeter and atmospheric profiler scheduled to be launched in December 2001 as part of the Earth Observing System (EOS) mission. For the surface altimetry measurements, the mean elevation of the laser's surface spot will be estimated from a centroid of the return pulse. To permit the determination of mass balance changes, individual ice-sheet altitude measurements must be made with uncertainties smaller than 10 cm. A number of factors affect the accuracy of the altitude measurement, including surface slope, atmospheric propagation and signal noise. A cross-over technique that averages the elevation differences at selected points on the ice sheets is designed to reduce errors in order to measure mean ice elevation changes to an accuracy of 1.5 cm per year, the stated goal of the ice-sheet altimetry [4].

In Part I of this paper ([1] hereafter referred to as DSE), the authors presented calculations of path delays by cloud and aerosol scattering from an analytic double-scattering model and Monte Carlo simulations of lidar surface returns. Both methods demonstrated that multiple scattering by thin polar clouds could seriously bias the altitude ranging of GLAS. For example, if the surface height were measured from the centroid of the return pulse, a thin arctic stratus cloud with an optical depth of 0.5, a mean particle radius of 6 microns, and a thickness of 3 km would produce a to-and-fro path delay of 30 cm, corresponding to an altitude bias of 15 cm.

Since the effect of multiple scattering is to always introduce a delay, the mean height change will be affected by the changes in cloud and aerosol layers in the atmosphere. If not corrected, seasonal and annual variation in cloud properties could significantly affect the determination of changes in the surface height. Surface altimetry is the primary objective of the GLAS mission, and multiple-scattering induced delay in the observations has the potential to seriously undermine this goal. Using current knowledge of Antarctic cloud properties, we study the impact of multiple-scattering on the determination of surface altitude, as well as on the interannual variability of it. The use of the atmospheric lidar signals of GLAS to eliminate such errors will also be discussed.

2. Variability of Cloud Properties on the Antarctic Plateau

The purpose of ice-sheet altitude observations is to measure temporal changes in ice thickness. A ranging bias would not be a problem if polar cloud properties were constant over time. Therefore, the critical issue is to determine the potential bias effect from seasonal and interannual variability of cloud properties. DSE found that several cloud parameters can affect the magnitude of multiple scattering-induced delays, including cloud optical depth, cloud particle size, and mean cloud height. The variability in each is now considered in turn.

2.1. Cloud Cover

Due to the harsh conditions in the Arctic and Antarctic, as well as their remoteness, observations of polar cloud properties have been far fewer than elsewhere. Even the most comprehensive cloud surveys such as Hahn et al. contain only sparse cloud data from the ice sheets over Greenland and Antarctica [2]. Despite this, some estimates of polar cloud characteristics can be made from current knowledge of polar cloudiness. The surveys of Hahn et al., for example, summarize surface observations of cloud cover across the globe. The observations indicate spatial variations in cloud cover over the poles. They are summarized from routine surface observations of sky conditions made by observers at various weather stations around the world. Mean annual values of Arctic cloud cover - which records the presence of clouds regardless of the fraction of the sky filled by them - from Hahn et al. [2] are shown in Figure 1. The values are typically between 70 and 80 percent, with cloud cover greater than 80% in the area around Spitsbergen, and smaller amounts (between 55 and 70 percent) over western Greenland and northern Canada.

Most surface observations of cloud cover over Antarctica are from coastal stations which report values from 70 to 80 percent, while the few stations located in the interior of the continent report lower cloud amounts, typically varying between 40 and 60 percent. Observations of entirely clear skies are rare at the high latitudes; even stable surface temperature inversions under clear skies usually lead to the formation of near-surface ice crystals, known as diamond dust. The mean annual frequency of clear sky observations in the Arctic Ocean and the coastal stations of Antarctica is usually less than 10 percent [6].

Cloud cover varies seasonally over the poles. Hahn et al. find that in winter, the cloud cover over most of the Arctic Ocean ranges from 50 to 70 percent. Arctic cloud cover is generally higher during the summer, when values range from 65 percent over western Greenland to over 80 percent over the Siberian Arctic. A similar seasonal cycle occurs over Antarctica, with higher values during the summer, and lower values during the winter. Mean wintertime cloud cover over the South Pole ranges from 30 to 40 percent, while in the summer, cloud cover varies from 45 to 70 percent at interior stations. Observations between 1971{1980 at the coastal Syowa Station (69 S, 39 E) show a more complicated seasonal variability incloud cover, with a maximum in the late summer of 79 percent and minima in the early summer (53%) and winter (60%) [3].

Hahn et al. also determined the interannual variation (IAV) in cloud cover over the poles [6]. IAV was defined as the standard deviation in seasonal cloud cover for the period from 1982-1991. The interannual variation in June-July-August (JJA) cloud cover for land stations in the Arctic was usually near 5 percent, and was near 10 percent for December-January-February (DJF) observations. Wintertime observations over the Arctic Ocean show IAV values from 20 percent north of Alaska to 2 percent over Spitsbergen. During the summertime the standard deviations ranged from 2 to 5 percent. The interannual variations at the Antarctic coastal stations and at the South Pole are generally near 5 percent.

The most recent year-long study of clouds over the Antarctic plateau is that of Mahesh *et al.* (2001, in press, [8,9]). From ground based longwave spectral observations of clouds at South Pole station in 1992, the authors obtained an annual cycle of cloud base heights, particle effective radii and optical thicknesses. This study was not specifically designed to quantify fractional cloud cover throughout the year; their spectrometer had a limited field of view and this was maintained constant throughout the year to consistently record clouds in the same direction. Mahesh et al found clouds in approximately 43% of their spectral observations, roughly consistent with Hahn et al.'s multi-year average.

2.2. Cloud height and optical depth

Over much of the Antarctic plateau, surface observations of cloud cover are constrained by the absence of topographical reference points. Mahesh et al. use a modified version of the CO_2-slicing method to determine the base height of clouds, from longwave spectral observations. The cloud bases have a bimodal distribution, with the primary maximum in the surface-based inversion layer, and a seasonally dependent secondary maximum between 2.0 and 2.5 kilometers. The higher clouds, i.e. most of the clouds with bases in the 2.0 - 2.5 km range have smaller optical depths (less than 1), whereas clouds with bases near the surface are often thicker, although many of these too have optical depths of less than 2.

Ice crystal precipitation can have a wide range of optical depths, but it is commonly much thicker during the winter. Wilson et al. report wintertime observations of ice crystal optical depths between 2.7 and 10.7, although thicknesses as large as 21 have been measured [10]. In the Arctic springtime, the observed thicknesses ranged from 0.015 to 1.9. Mahesh *et al*.'s findings of cloud optical depths confirmed the generally held view that clouds over the Antarctic plateau are much thinner than those at the coasts of the continent. Nearly 95% of the clouds at South Pole station were seen to have optical depths smaller than 5.

2.3. Cloud particle size

The multiple-scattering induced path delays will also depend on the microphysical properties of the clouds. Curry et al. report that the most comprehensive measurements of wintertime Arctic ice crystal distributions show modal radii between 10 to 80 ?m, and an average effective radius of 40 ?m [4]. Summertime Arctic stratus, on the other hand, have much smaller mean radii, ranging from 2 to 7 microns.

In the Antarctic, Smiley et al. report that the most common sizes of clear-sky ice crystal precipitation observed during the wintertime are between 50 and 200 microns [5]. However, crystals smaller than 50 microns could not be reliably measured on their particle replicator, and smaller particles were not reported. Stone infers cloud properties of Antarctic clouds during the wintertime from radiometric profile measurements, and estimates most clouds are optically thin and composed of small particle sizes on the order of 4 to 16 microns [6]. Lubin and Harper retrieve cloud particle sizes using AVHRR infrared radiances, and estimate that the mean summer and winter effective radii over the South Pole are 12.3 and 5.6 ?m, respectively [7]. Mahesh et al. determined cloud particle effective radii from their 1992 data, and obtained a median particle size of 15 ?m; in their study, the effective radii of particles larger than 25 microns could not be accurately determined, and only a lower limit to those particles is given. A particular seasonal pattern observed here indicated that cloud particle sizes in winter mostly ranged between 10 and 20 ?m, whereas in summer larger particles, with effective radii larger than 25 ?m, were dominant [8,9].

3. Computation of altitude biases

3.1. Results

The observations summarized in Section 2 indicate some variability in polar cloud properties that would lead to seasonal and interannual variation in the altitude bias. To estimate the mean altitude bias for a particular period, the Monte Carlo path delay results from DSE can be weighted by the climatological frequency of various cloud types.

The mean altitude bias for a given period is defined as:

$$\bar{B} = \frac{?_i ?_j ?_k ?b??_i, h_j, r_k? ?F_T??_i, h_j, r_k?}{?1 - F? + ?_i ?_j ?_k ?F_T??_i, h_j, r_k?}$$

where $b(?_i,h_j,r_k)$ is the computed altitude bias for each transmissive cloud based on cloud optical thickness ?, cloud height h, and cloud particle size r, and $F_T(?_i,h_j,r_k)$ is the cloud coverage fraction as a function of those same variables for each transmissive cloud. F is the overall cloud cover fraction, $?_i$ is the distribution of cloud optical depths, h_j is the distribution of cloud heights, and r_k is the distribution of cloud particle sizes. Altitude biases thus obtained can be examined for seasonal or interannual variation, computed as the difference between the mean bias from one season (year) to the next:

In this paper, we obtain altitude bias estimates from Monte Carlo calculations using cloud properties reported by Mahesh et al.; these include optical depths (?), cloud heights (h) and cloud effective particle radii (r) derived from infrared spectral measurements made from the ground in 1992. Following equation (1), an altitude bias can be computed for each measurement using these properties, and mean altitude biases over different seasons as well as the entire year can also be obtained. GLAS will likely see cloud conditions over the Antarctic Plateau that are not identical with those from 1992; nevertheless these data represent the best combination of several cloud properties relevant to multiple-scattering induced delay from the same set of clouds; also, at this time, Mahesh et al.'s findings are the only available year-long dataset of cloud properties.

Not all clouds will contribute to the altitude bias since many will be too thick to be penetrated by the GLAS lidar. According to the specifications of the GLAS mission, clouds with a two-way transmissivity of less than 0.25 would not included in any altimetry estimates. For the geometry of the GLAS lidar, the Monte Carlo calculations by DSE show that when forward scattering is considered the optical depth limit corresponding to the above transmissivity is as large as 2. At South Pole, this upper limit to cloud optical depth still permits the use of nearly 75% of the observations from 1992. However, since the scattering-induced delay increases in magnitude with optical depth, one might limit scattering error by using only those observations where clouds are not very thick, say, with a smaller optical depth, such as 1.0 or even 0.1. The drawback in such an approach is that an increasingly lower threshold of acceptable cloud optical depth eliminates greater numbers of the observations from consideration. Nevertheless, results are presented here for such subsets of clouds with smaller optical depths, to show that more accurate altimetry from a selected subset of the measurements is possible.

Figure 2 shows the scattering-induced altitude biases expected in GLAS measurements using sky conditions recorded by the interferometer in 1992; histograms are plotted for all observations (2a) as well as for the cloudy cases alone (2b). The large peak of observations with little or no scattering-induced bias in Figure 2a is primarily due to observations of clear-sky, which comprise 57% of the measurements, the remainder are from clouds whose scattering effect is minimal. For the clear-sky observations, it was assumed that the scattering-induced bias is zero, this is explored further in a later section.

Using cloud properties obtained by Mahesh *et al.*, Monte Carlo calculations were performed to obtain the altitude bias that would result, from each combination of cloud height, particle radius and optical depth. Consistent with indications from radiosonde data taken during the year, a typical cloud thickness of 1 km was used in the modeling.

Mahesh *et al*. determined only a lower bound in particle radius in a number of summer-time cases, and in a few mostly winter cases of thick clouds, only a lower limit to the optical depth was determined. The Monte Carlo calculations used to obtain the values in Figure 2 were run only for those observations of clouds (approximately three-fourths of the total number of clouds observed) in which both particle radius and optical depth were known. The entire dataset of values, including those omitted in Figure 2, is shown in Figure 3, where the instances of observations using lower limits are specifically indicated as those with only a lower limit to optical depth (diamonds), those with only a lower limit to particle size (open circles) and those with only a lower limit to both particle radii and optical depths (filled circles) known. In these special cases, it must be assumed that the altitude bias corresponding to scattering-induced delay is at least as large as indicated in Figure 3. The median value of the altitude bias for the entire year, from only the cloud observations, is 10.8 cm, and the mean is 16.2 cm.

For a given value of the optical depth, the bias in altitude can be expected change due to variations in both particle size and in the height of the cloud above the surface. Low clouds scatter photons which, despite the scattered path, still remain within the field of view of the instrument. Scattering by higher clouds, which are more common in the non-winter months (October-March), tends to remove the scattered path lengths from the field of view, thereby biasing the altitude less. With increasing particle radius, however, a cloud of a given optical depth will bias the altitude increasingly. The winter altitude biases in Table 3 (discussed in a later section) are smaller than non-winter values; this suggests that the effect of particle sizes in the non-winter months is more significant than the fact that in winter, clouds occur nearer the surface.

3.2. Variability in altitude bias.

If the altitude bias were invariant from one year to another, errors introduced into altimetry measurements as a result of multiple scattering could be neglected, since the objective, namely to determine interannual changes in elevation, could still be fulfilled. However, since the properties of clouds which cause delay by multiple scattering are not constant from one year to the next, the bias varies as well. The interannual bias can vary due either to changes in the frequency of cloud covered observations, or due to the extent of the sky covered by clouds being different. More significantly, the bias values are sensitive to changes in the specific microphysical and radiative properties of clouds from one year to the next; as an example, we will consider how these numbers are affected if all variation in cloud properties is contained entirely in optically thick or thin clouds only. We will examine the variability in interannual bias using two different approaches; to understand the impact of these different variables.

In the first method, we use cloud observations from the spectral measurements of Mahesh et al. and the inter-annual variability in cloud cover obtained by Hahn et al. These observations and their findings will permit us to examine how inter-annual changes in the bias result from the occurrence of clouds. In the second approach, we obtain from routine synoptic reports the averages of the *fraction* of the sky covered by clouds during 1992-94, and the interannual bias changes that would result from variations in the cloud fractions.

3.2.1 Variation from spectral observations made during 1992

To estimate the uncertainty in altimetry that will result from such variability, we may consider the average, as well as the extremes of variability in cloud cover over the Antarctic plateau. The average interannual variation in summer cloud cover at the South Pole from Hahn et al. is about 5 percent, while it is 11 percent during the winter [2]. To assess the impact of this variation on altimetry measurements, we must additionally know the variation in their optical thicknesses, particle sizes, and the heights at which they occur. If in any given year the additional (or fewer) clouds seen are negligibly different in their average properties than those seen in the 1992 dataset, then we may well see no change in the altitude bias using data from a different year. If, on the other hand, there is variation in the cloud properties, which on average is different from those seen in 1992, the average biases computed in Table 1 will increase or decrease correspondingly.

By assuming how this variation is distributed among various optical depths, we can assess the variability in the interannual bias, and its potential impact on altimetry measurements. Whereas this procedure is not intended to produce an estimate of the average variability in the bias, it nevertheless gives us an idea of the bounds of such variability. By removing (or adding) the clouds with the most and least impact on altitude biases from the 1992 data in proportion with the estimated variability in the cloud cover (5% in summer, 11% in winter), we can obtain new annual average bias values.

The altitude biases obtained by considering such deviance from the optical depths seen in 1992 are tabulated in Table 1. As is expected, the addition of thick clouds increases the values of the seasonal and annual altitude biases, as does the removal of thin clouds. Conversely, the addition of thin clouds, or the removal of thick clouds, reduces the average altitude bias. Both the seasonal numbers as well as the annual average change in the altitude bias from 1992, shown in the last column of the table, are greater than the GLAS mission requirement value (1.5 cm) itself.

A second calculation can also be made using the maximum reported variability (13% in summer, 27% in winter) in inter-annual cloud cover instead of the average values, also from Hahn et al.'s measurements. As was done in obtaining values for Table 1, in this case too, the additional (or fewer) clouds are viewed to be entirely of the extreme optical depth regimes, and the annual average biases in the altitude are computed again; these numbers are shown in Table 2. Expectedly, the seasonal and annual bias values are now even more different from the 1992 numbers, up to three or four times the GLAS mission specification.

These numbers suggest that the average variation in cloud cover and optical thickness from one year to another, using a multi-year average estimate of such variability from Hahn et al., is produces variation in the altitude bias that is significant. The values of such variability, being comparable to or greater than the GLAS mission specification, will clearly impede the reliable determination of altitude changes from one year to the next. Indeed, the most advantageous of the various changes considered in Tables 1 and 2 still produces bias variations of 1 to 1.5 cm.

Similar assessments can also be made with changes in particle sizes instead of or in addition to optical depth changes. The results for which we have shown results in Table 1 and 2 implicitly assume that any additional or less cloud cover in other years will have other important cloud characteristics (cloud heights and particle sizes) distributed seasonally the same way as in 1992; the potential impact of changes in those characteristics, though, cannot be overlooked. However, our intention here is to suggest that variability in cloud cover can manifest itself in variations in the altitude bias of GLAS measurements from one year to another. Without quantifying the potential impact on altitude bias from every conceivable change in cloud characteristics, we have attempted to define some range of values to such variability. This effort appears to show that variation in the altitude bias could be of the same magnitude as the accuracy requirement specified for the GLAS mission itself. Thus, a determination of altitudes, already uncertain due to the presence of clouds, must additionally be reconciled with year-to-year changes in the uncertainty in such measurements.

3.2.2. Variability from synoptic reports of fractional cloud cover

The multiple-scattering induced delay results not only from variation in cloud occurrence, which we examined in the previous sub-section, but just as likely from changes in fractional cloud cover from one year to the next. An alternate approach to obtaining the interannual variability in the altitude bias is to use fractional cloud cover information reported by surface observers on a regular basis, and to assume that variability in cloud occurence is distriibuted across all optical depths, and not merely within the extreme optical depth regimes as we assumed in the previous section.

The routine surface observations and synoptic reports that contain cloud cover data, in contrast to the ones of Mahesh *et al.*, are made visually and without the advantage of reference heights in the uniform topography around South Pole station; this precludes the accurate knowledge of cloud heights, particle sizes and optical depths. However, this set of observations includes the advantage of having been made over many years. Also, unlike the spectral measurements, the visual observations are not limited to the particular line of sight. For these reasons, the multi-year observations provide some information that is more representative of typical conditions at the pole during any given year.

In Section 3.2.1, we obtained the interannual variability in the altitude bias due to variation in cloud cover from one year to the next; in this section we determine the variability that would result from variations in the cloud fractions. Whereas cloud cover is the percentage of observations during a given period which included clouds that filled the sky either partially or wholly, cloud fraction is the portion of the sky from each observation that is filled by clouds.

From the WMO synoptic reports from South Pole station, values of fractional cloud cover, and the variability in the values, were obtained for the winter months of the years 1992-94, as well as for the non-winter months. The average cloud cover fraction for the three year period around the 1992 data was 42% during the winter months, and 52% during the other months. Inter-annual variability in these values (as measured by the standard deviation) is slightly larger (11.5%) in the winter than in the rest of the year (8.1%). Using the seasonal average altitude biases obtained in Section 3.1, the corresponding increases or decreases that would result from changes in cloud fractions can be computed. The variations in cloud cover fractions correspond to variation in the interannual bias of 0.75 cm during the winter months, and 0.85 cm during the rest of the year; this results in an average interannual variability in the bias of approximately 0.8 cm.

These numbers are lower than the values we saw in section 3.2.1; this is expected, since in this case we have distributed the variability across clouds of all optical depths. Very (optically) thin and thick clouds represent the extremes at which the ranging delay is least and largest respectively, and the average of changes at these extremes is expected to be larger than when variations are considered to be manifest across clouds of all optical thicknesses.

3.3. Methods to reduce bias

The results presented so far assume the altimetry measurements will be used as a “standalone" measurement, with no information available on cloud properties. However, if the optical depths of the clouds under observation were known, then we could select those instances when the optical depths are small enough that the altimetry errors expected from them are small; indeed knowing the optical depth, we may even be able to correct some of the altitude bias. The use of data from the 532 nm (green) channel on GLAS does provide the necessary information to facilitate this reduction or elimination of bias in altimetry. Cloud optical depths can be obtained from the green channel if clouds are sufficiently thin so that a lidar signal is detectable both above and below them [12]. The limiting optical depth for such analysis is between 1 and 2, and a substantial fraction of Antarctic clouds are transmissive enough to permit such a determination of layer optical depth.

Using optical depths so determined, the altitude bias could then be reduced by setting a cloud optical depth threshold for acceptable GLAS observations. Additionally, biases could be reduced by using a more sophisticated method to analyze the lidar surface returns. Both approaches are discussed below.

From the entire set of observations, subsets can be selected using lower optical depth thresholds. Table 3 shows the seasonal and annual values of the altitude biases obtained using several different thresholds - 0.1, 0.5, 1.0 and 2.0 - along with the numbers from all observations. Since very few clouds at South Pole (approximately 10-15%) have optical depths larger than 2, the bias obtained with the cloud optical depth threshold set to 2 is not significantly different from the bias obtained from all the data. However, as the optical depth threshold is lowered, the altitude bias drops correspondingly. The values in altitude bias obtained at the lowest threshold shown (0.1) approach the GLAS requirements to detect secular changes in ice thickness as small as 1.5 cm a year. Limiting the computation of altitude bias to such cloud-free or nearly cloud-free observations also largely removes the interannual variability in altitude bias.

An alternate approach to limiting the bias in estimated altitudes is to use a more sophisticated algorithm to analyze the GLAS measurements. The Gaussian fit method described in paper 1 (DSE), for example, eliminates a significant fraction of the scattering-induced delay. Table 4 shows calculations of scattering-induced delays obtained from this method; this table is readily comparable to Table 3. The median altitude bias obtained with this fit is nearly 40% smaller in winter, and one-third smaller during the other months; the mean values are reduced by even greater amounts. At very low optical depths, the altitude bias averaged over the entire year is within the GLAS mission requirement of 1.5 cm.

d. Observations under blowing snow conditions

As stated earlier, the altitude bias can be held to small values if we selectively exclude observations that include clouds of relatively large optical depths. It will be especially advantageous, in fact, to limit the determination of altitude to those observations which are made under known cloud-free conditions. The use of the atmospheric channel on GLAS will permit such a determination, so that the 1064 nm channel is not used as a standalone observation. There is, however, an additional concern, namely blowing snow.

Throughout much of the Antarctic plateau, downslope surface winds known as katabatic winds are prevalent during much of the year. The settling of cold air at the higher elevations of the plateau creates these surface winds, which can disturb loose and recent snow. Visual observations made by the surface weather observers at South Pole station indicate blowing snow conditions in up to a third of all observations [11]. Blowing snow is typically not very optically thick, and spectral measurements used in Mahesh *et al*. suggest that an optical depth of 0.1 is as thick as the snow may be.

The concern for GLAS, however, is not the optical depth of the snow, but its proximity to the surface. Blowing snow typically extends from the surface up to the lowest 50-300 meters, and a special operational mode to process GLAS data at 50-m resolution is needed to detect these thin near-surface layers. When a scattering layer is close to the surface photons scattered by it nevertheless remain within the footprint of the GLAS measurement. As a result, the delay in their travel times caused by such scattering becomes included in altimetry calculations. This means that even if GLAS altimetry is limited to nearly or entirely cloud-free conditions as determined using the 532 nm channel, the altitude values obtained from them might be in error.

Using a typical value (100 microns) for the snow particle radius, and several combinations of physical and optical thicknesses for the blowing snow layer, Monte Carlo calculations were performed as before to obtain an estimate of the altitude bias due to blowing snow. Figure 4 shows the altitude bias due to blowing snow for two different optical depths (filled circles and squares) at several different physical thickness values for the snow layer. Also shown are the lower bias estimates obtained when the calculations are repeated with the Gaussian fit (corresponding open circles and squares) described in DSE. A blowing snow layer 50-100 m thick with an optical depth between 0.05 and 1.0 will bias the altitudes derived by between 2 and 4 cm approximately; this bias can be considerably reduced (to between 0.5 and 1.0 cm) by the use of the Gaussian fit method to determine the centroid of the return pulse. Even these reduced values, it must be borne in mind, average to more than a third of the specified accuracy needed for the GLAS mission.

4. Summary and Conclusions

Atmospheric multiple scattering is potentially a large error source for precision laser measurements of surface altitude as envisioned for the Geoscience Laser Altimeter System (GLAS) or other similar space missions. Also, a survey of polar cloud observations indicates that most of the cloud properties that will affect spaceborne lidar measurements have significant seasonal and interannual variations. Using a recently completed study of Antarctic cloud properties, the potential impact of such clouds on GLAS altitude measurments is quantified. The likely inter-annual variability in altitude bias that results from year-to-year variation in the relevant cloud properties is also determined. These calculations suggest that the atmospheric scattering effects on GLAS measurements are not insignificant.

Using cloud properties dervied from obsevations made at the South Pole as well as the path delay data from DSE, estimates of the mean Antarctic summer and winter altitude bias were computed. From the interannual variability in cloud cover and cloud fraction estimated by surface visual observers, the likely year-to-year variation in the altitude bias was also obtained. The bias in altitude introduced by clouds in the path of the lidar pulse appears to be significant, and is often larger than the accuracies specified for the mission. Further, interannual variability in the bias itself is substantial; and a uniform altitude bias cannot be subtracted out of observations made.

However, altimetry measurements can be confined to those observations made from the satellite which are known to be under cloud-free or thin-cloud conditions; this reduces the altitude bias a great deal. To overcome the limitations in altimetry measurements caused by the bias resulting from scattering within cloud layers, ice sheet elevations should thus be determined only from cloud-free observations. This can be achieved using the atmospheric channel at 532 nm for cloud-detection, alongside the 1064 nm channel's altimetry capability. The use of improved waveform analysis techniques, more sophisticated than merely accepted the centroid of return pulses, can further reduce the biases.

Despite the selective use of clear-sky conditions for altimetry calculations, near-surface blowing snow conditions which occur frequently will remain unaccounted for. The proximity of the snow to the surface makes this scattering layer more potent (per unit optical depth) than clouds, since scattered, delayed photons remain within the field of view of the instrument. An altitude bias of 1-3 cm from the snow layer alone is likely. However, as with clouds, the use of improved methods to analyze the return pulse will help in substantially reducing the bias under blowing snow conditions.

The upcoming GLAS mission, by monitoring ice-sheet altitude changes over Antarctica and elsewhere, is expected to provide information on whether global warming is affecting a sensitive and important part of the planet. Potential melting of high-latitude ice sheets from warming will likely lead to significant rises in sea level, and consequently to catastrophic outcomes along coastlines around the world and in many island nations. This paper suggests that the measurement accuracies necessary to permit the required monitoring are achievable under conditions of thin or no cloud cover. Careful selection of data from which GLAS altimetry measurements are made is therefore necessary to ensure that ranging delay due to scattering is accounted or corrected for.

A factor that has not been included in this analysis is the effect of surface slope on the altitude bias. The results of DSE suggest that sloped surfaces may obscure the effects of cloud multiple scattering on the path delay, and make the determination of the return pulse centroid more difficult. In addition, other factors such as signal noise and surface roughness have not been examined. These factors may also reduce the effectiveness of Gaussian fitting on the path delay, and other forms of return pulse analysis may be required to reduce altimetry biases to acceptable levels. Further study is necessary to determine how signal noise, rough, sloped surfaces and advanced waveform analysis of the return pulse may affect the multiple scattering-induced altitude bias.

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List of Figures

Figure 1. Mean annual cloud cover over the Arctic derived from [2].

Figure 2. Histogram of scattering-induced altimetry errors obtained by Monte Carlo calculations, using cloud properties obtained from interferometer measurements made during 1992. The upper panel (a) includes observations of both clear-sky as well as cloudy conditions; scattering-induced delay under clear sky conditions is assumed to be zero. In the lower panel, only the cloudy cases are considered separately. The median value of the scattering induced bias from only the cloudy-sky observatrions is 10.8 cm.

Figure 3. Multiple-scattering induced altitude bias from all observations of clouds during 1992, obtained by Monte Carlo calculations. The pluses (+) represent data when both cloud optical depth and particle radius are known. In other cases, only a lower limit to the scattering induced delay is calculable, either because only a lower limit to the optical depth is known (diamonds), or only a lower limit to the particle effective radius is known (open circles), or both (filled circles).

Figure 4. Scattering-induced altitude bias from blowing snow. Results are shown for two different optical depths, using both the centroid of the return pulse, as well as the Gaussian fit discussed in DSE. The filled circles are at an optical depth of 0.1 and the filled squares at an optical depth of 0.05; each of these were obtained from the centroid of the return pulse. The corresponding values obtained from the Gaussian fit at the two optical depths, are shown as open circles and squares respectively.

Table 1: Altitude bias values, and changes in those values from 1992 annual and seasonal averages, assuming that *average* year-to-year variation in cloud cover (5% in the summer, 11% in the winter) is contained entirely in either thick (?>2) clouds or in thin (?<2) clouds.

	More clouds than in 1992		Fewer clouds than in 1992		Average variability from 1992
	thick	**thin**	**thick**	**thin**	
summer	23.04	20.39	19.40	22.33	1.37
winter	17.40	13.33	11.05	16.13	2.29
all-year	18.41	15.13	13.56	17.42	1.78

Table 2: Altitude bias values, and changes in those values from 1992 annual and seasonal averages, assuming that *extreme* year-to-year variation in cloud cover (13% in the summer, 27% in the winter) is contained entirely in either thick (?>2) clouds or in thin (?<2) clouds.

	More clouds than in 1992		**Fewer clouds than in 1992**		**Average variability from 1992**
	thick	**thin**	**thick**	**thin**	
summer	25.48	19.08	15.89	24.20	3.68
winter	20.65	11.90	4.01	19.23	5.99
all-year	21.20	13.82	8.66	19.73	4.61

Table 3: Seasonal and annual average values of multiple-scattering induced bias in surface elevation at South Pole, for several subsets of the measurements from 1992. The subsets are chosen using varying optical depth thresholds; as thicker clouds are excluded from consideration, the scattering-induced delay becomes smaller.

	WINTER (April-September)		**NON-WINTER** (October-March)		**All year** (1992)	
	Median	**Mean**	**Median**	**Mean**	**Median**	**Mean**
all clouds	8.66	14.57	14.46	21.31	10.82	16.18
? < 2	7.05	9.73	13.91	15.97	8.76	11.25
? < 1	5.29	6.46	10.49	10.79	5.97	7.25
? < 0.5	4.12	4.67	5.48	6.29	4.15	4.87
? < 0.1*	1.89	2.00	1.94	1.97	1.89	2.00

*Between October and March, i.e. during the non-winter months, no clouds were observed with optical depths smaller than 0.1, the values listed in the table are from the thinnest cloud observed during that period, on October 5, 1992, with optical depth 0.16.

Table 4: Identical to Table 3, except that the multiple-scattering induced biases were obtained in this case using the Gaussian fit method described in DSE**.**

	WINTER (April-September)		**NON-WINTER** (October-March)		**All-Year** (1992)	
	Median	**Mean**	**Median**	**Mean**	**Median**	**Mean**
all clouds	5.03	6.55	9.51	10.45	5.64	7.50
? < 2.0	3.85	4.76	9.17	8.42	5.03	5.65
? < 1.0	3.09	3.62	5.45	5.67	3.29	3.99
? < 0.5	2.49	2.75	3.14	3.48	2.53	2.85
? < 0.1*	1.19	1.22	1.71	1.71	1.19	1.22

* Between October and March, i.e. during the non-winter months, no clouds were observed with optical depths smaller than 0.1, the values listed in the table are from the thinnest cloud observed during that period, on October 5, 1992, with optical depth 0.16.